TRUTINOR

Trutinor:

A Next-Generation Earth Radiant Energy Instrument

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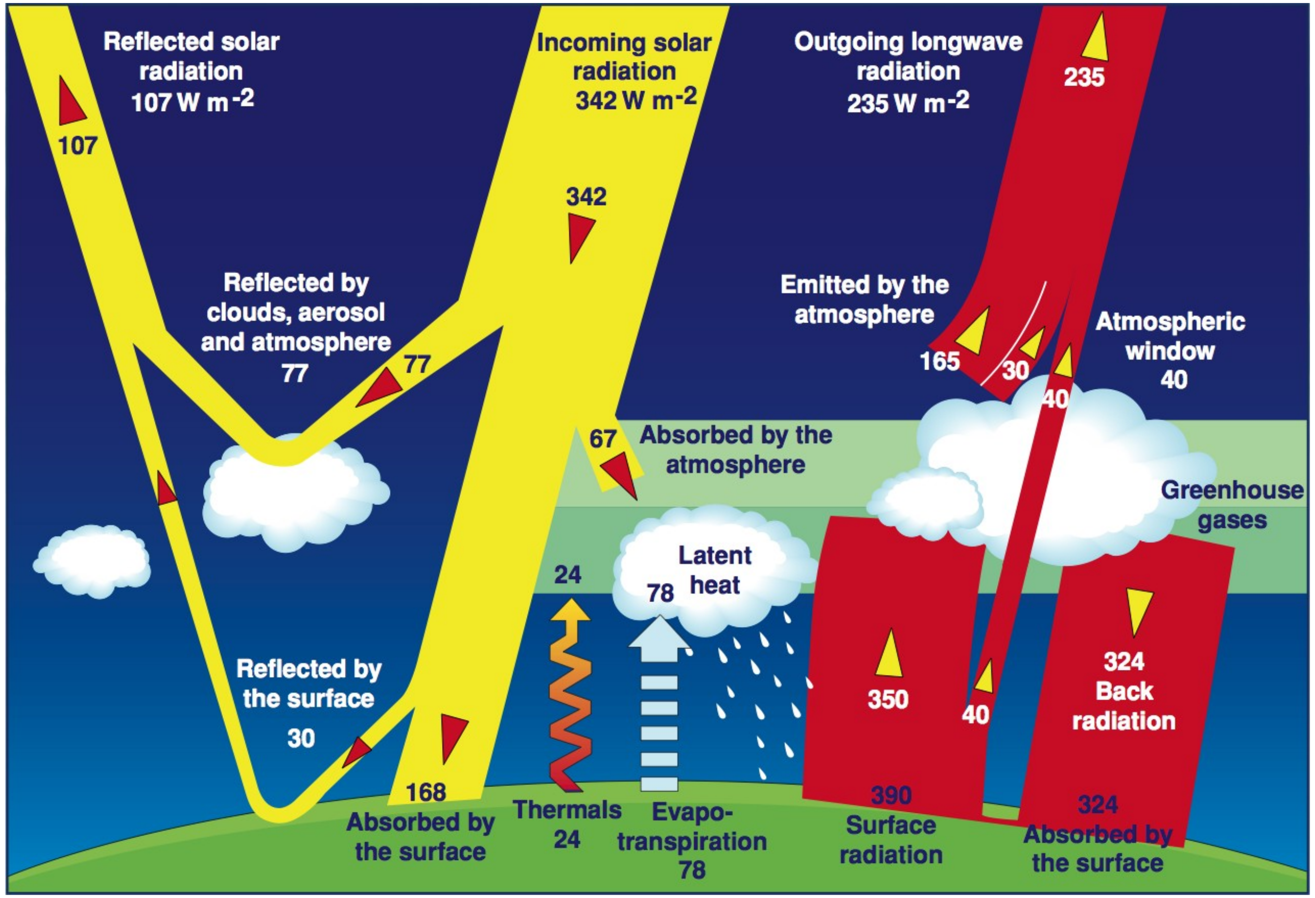
Outline:

- Science problem
- Mission need
- Requirements
- Instrument design
- Milestones and progress
- Impacts of COVID-19
- Path forward

Earth & Atmosphere Energy System

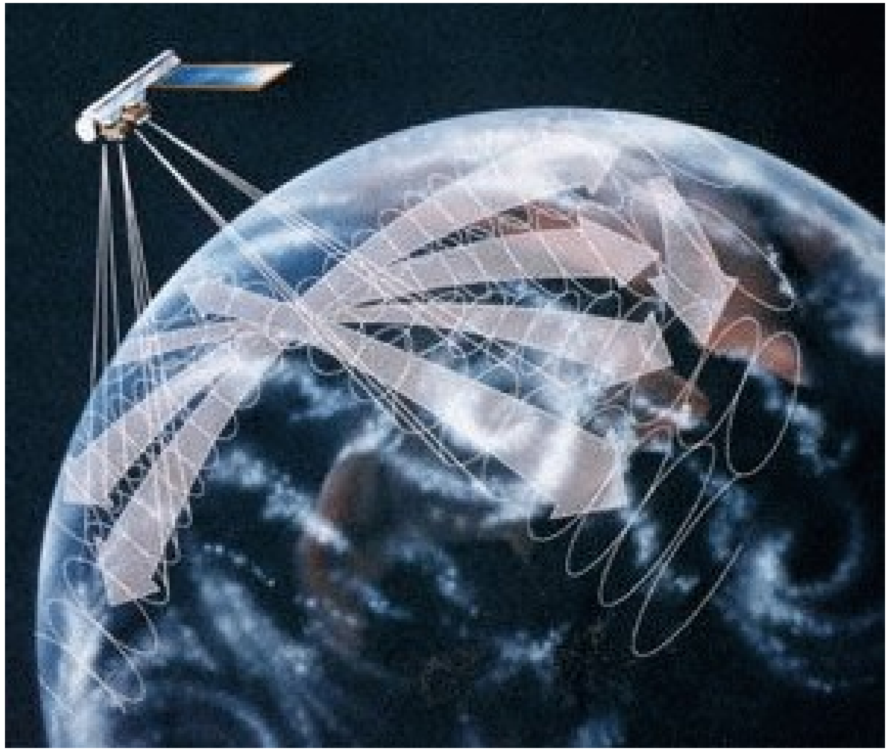


Calculate top of atmosphere (TOA) **Shortwave (SW)** and Longwave (LW) fluxes:

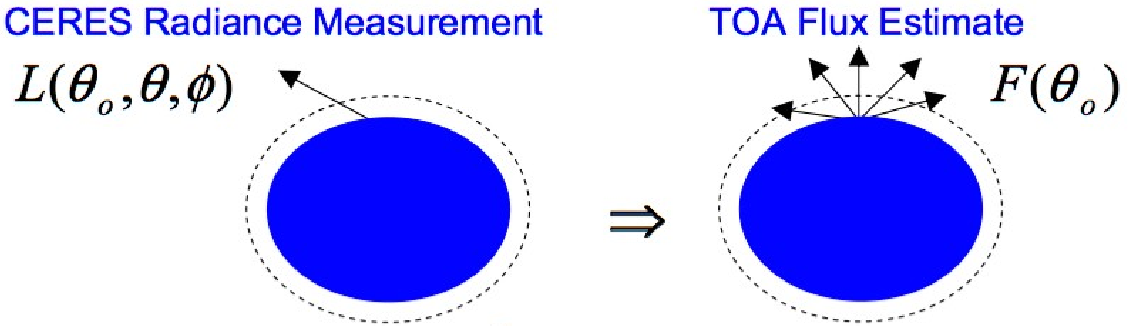
Fnet = Fdown – Fup

Ftotal = **Fnet, SW** + Fnet, LW

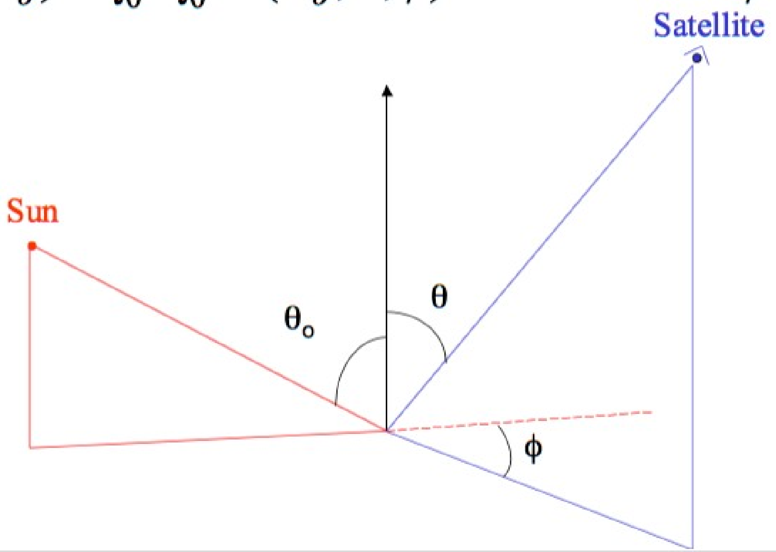
Flux inversion Requirements - ADMs



CERES data taking mode for ADMs:
Rotation Azimuth Plane (RAP)

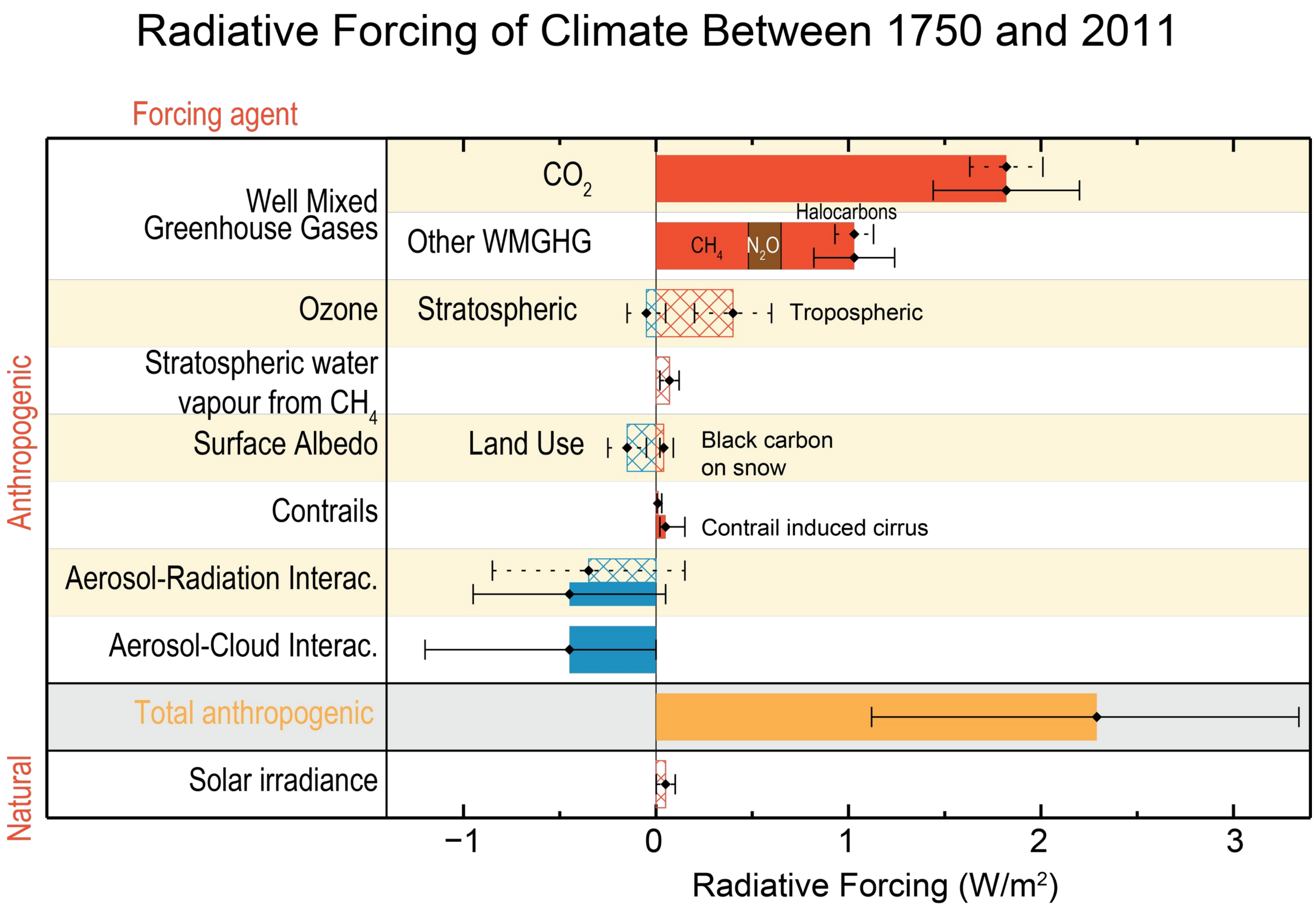


$$F(\theta_o) = \int_0^{2\pi}\int_0^{\frac{\pi}{2}} L(\theta_o,\theta,\phi)\cos\theta\,\sin\theta\,d\theta\,d\phi$$



ADMs are defined for every physical scene type

ERB data and Climate Change: Radiative Forcing



ERB data provides constraints on the climate forcing.

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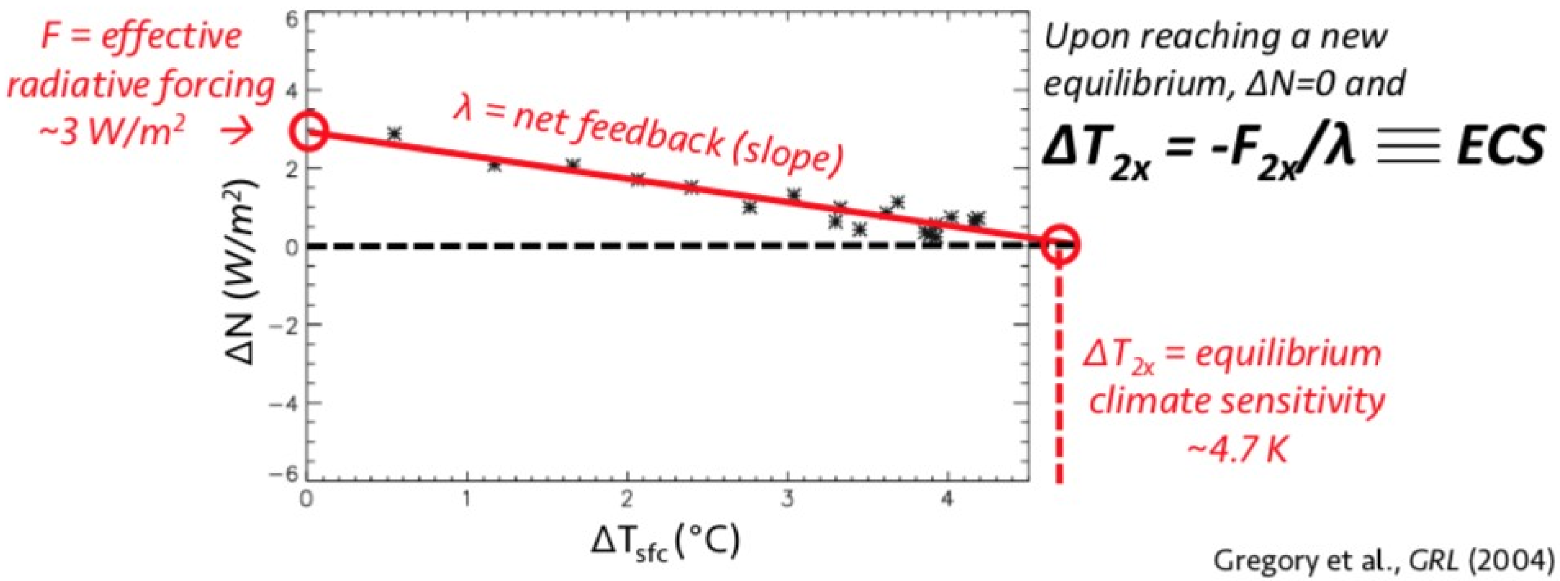
ERB data and Climate Change: Climate Sensitivity

- The key question is…how much will the climate warm per unit increase in radiative forcing?

TOA net radiation anomaly (N) is expressed as

$$\Delta N = F + \lambda \Delta T$$

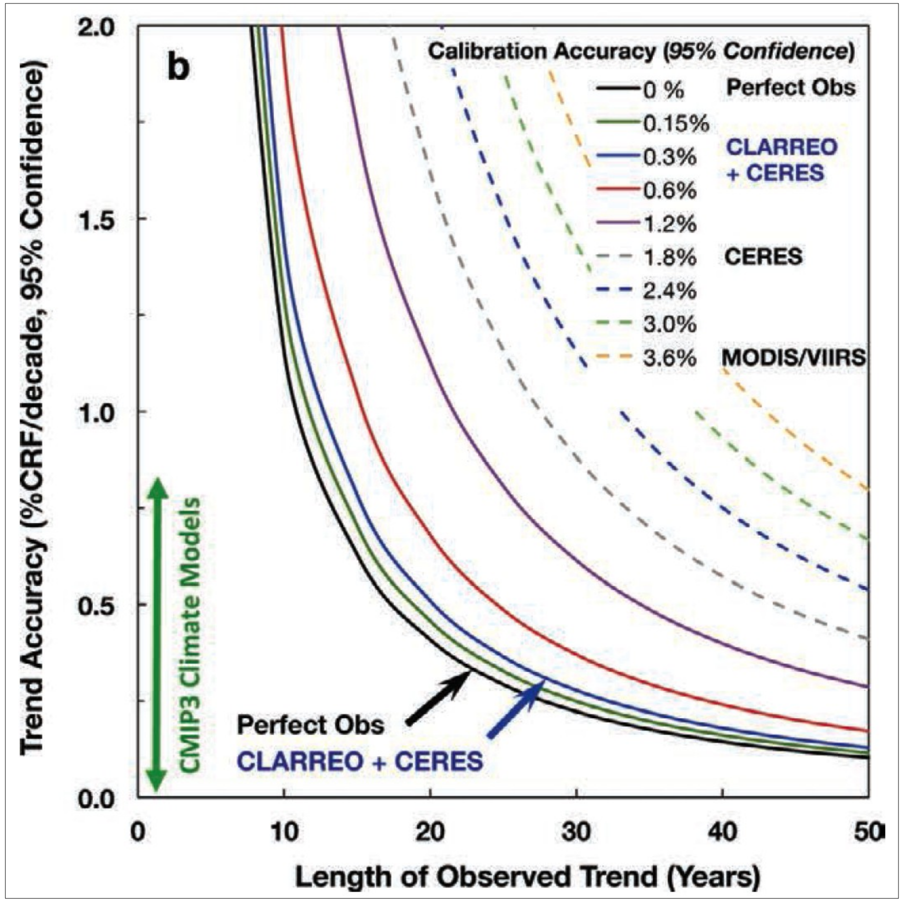
Sometimes referred to as the ”standard model for climate response and forcing”



Gregory et al., *GRL* (2004)
Andrews, et al., *Surv. Geophys.* (2011)

Monitoring the TOA ERB necessary to use this approach to constrain climate sensitivity.

It takes a long time to detect a trend in the data record



- Figure shows the quantitative impacts of observational accuracy on the ability to detect trends for climate variables (Shea et al., 2017). Wielicki et al (2013)
- As the accuracy of observing system increases, the time to detect a trend decreases

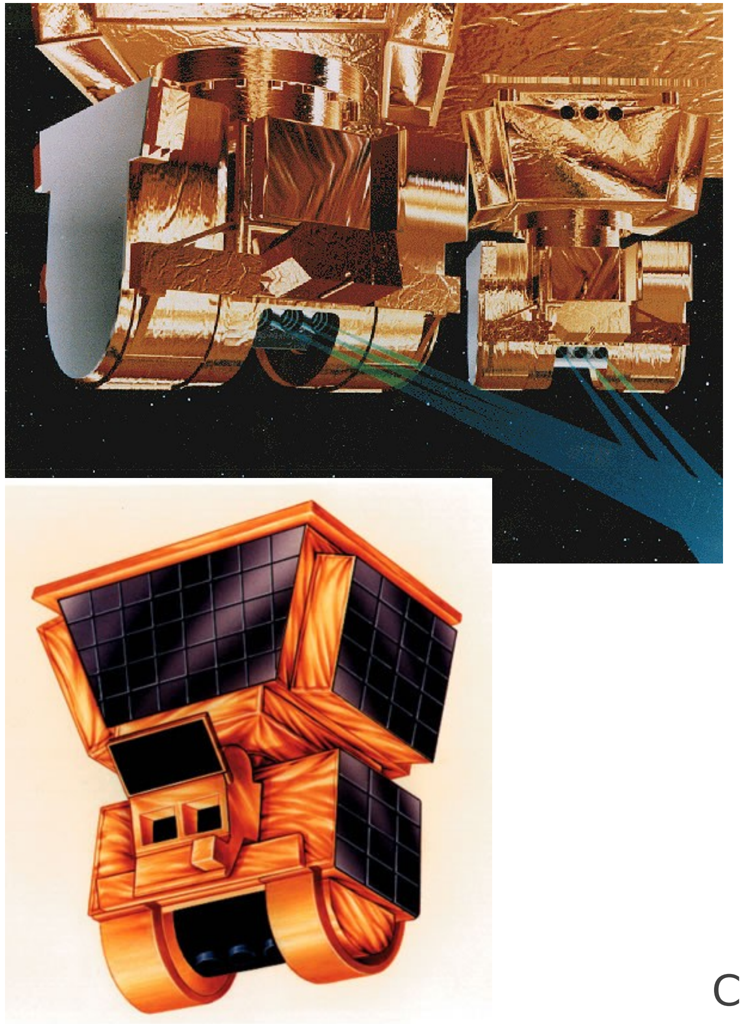
Long-term ERB Vision:

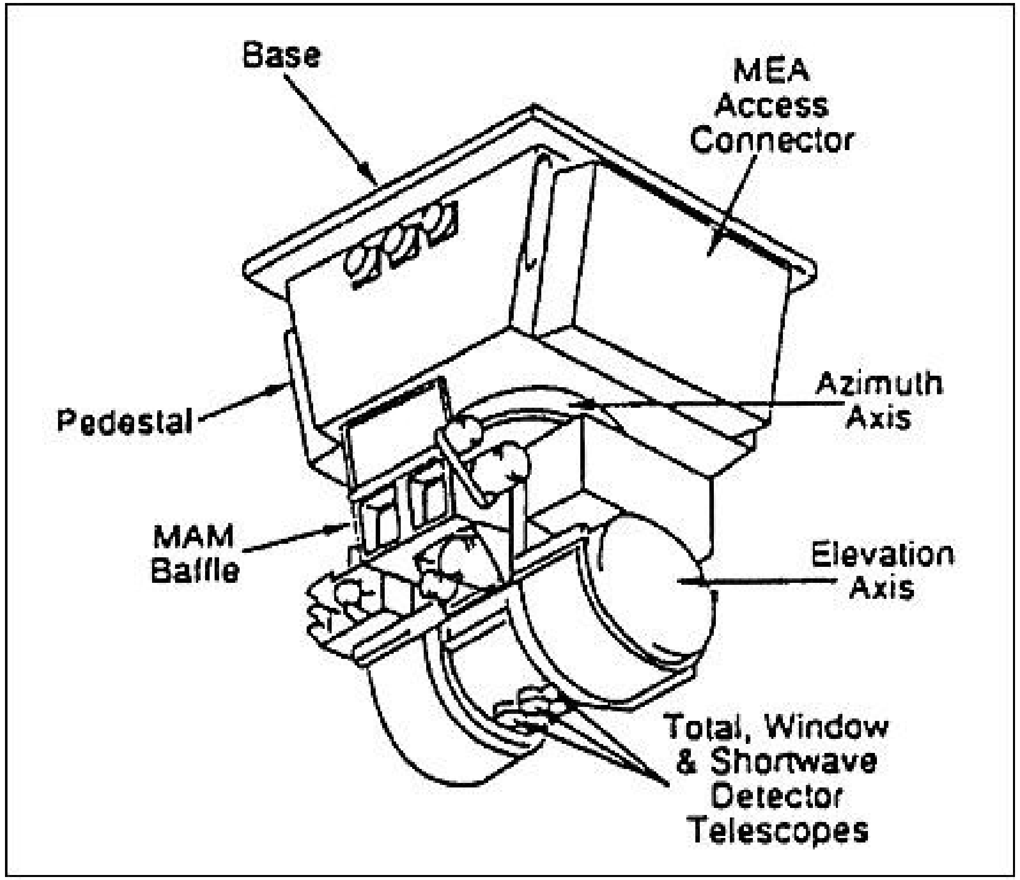
- The science and societal implications dictate the need for a continuous ERB climate data record from now into the foreseeable future.
- A gap would produce an irreparable effect (at least in our lifetime) on climate science.
- Current approach is costly.

Trutinor Philosophy:

- Enable a >100-year long, continuous ERB climate data record capable of resolving the key outstanding challenges in climate science (climate sensitivity, cloud feedback, and aerosol forcing) while providing a foundation for the next generation of climate scientists to pose new questions, through a sustainable, cost-effective instrument.
- Continuously update design as new technologies become available
- Design a highly accurate instrument to make the measurement as robust as possible against gaps.

CERES Instruments

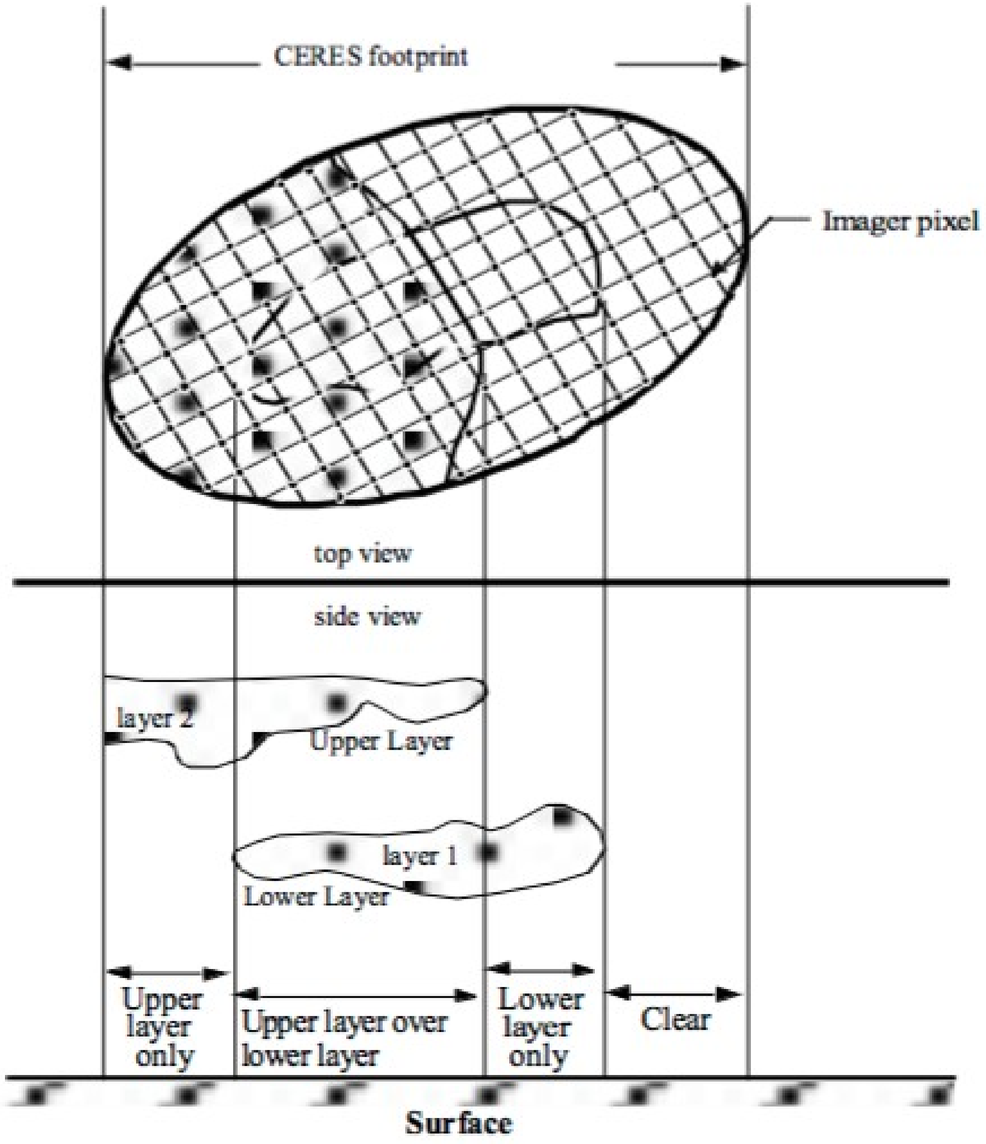




CERES instrument layout

CERES/RBI instrument layout is driven by accommodation requirements for Terra/Aqua/NPP/JPSS-1

CERES and Imager Measurements



SPATIAL:

- Near simultaneous measurements of CERES and Imager
- CERES FOV = 20/25 km at nadir
  (10 km on TRMM)
- Imager pixel = 1 km
  (4 km for VIRS/TRMM)

SPECTRAL:

- CERES is broadband
- Imager is spectral multi-bands

Mission Constraints

- Orbit maintenance and accurate pointing
- Ability to obtain imager information either by:
  - flying on the same bus or
  - in near-coincidence (~3 minutes, TBD)
- Measurement accuracy at least as good as for CERES
- ADM data collection (multi-angular sampling)
- Optimized (low) mission cost
- Free-flying satellite

Trutinor Science Traceability Matrix

Science Questions	Observables	Parameters	Instrument Requirements	Mission Constraints
How is Earth's climate changing and what is the role aerosols and clouds?	Longwave radiances	Spectral Range	5 - 50 microns	Minimum 3-year mission lifetime
		Dynamic Range	0 to 180 $W/(m^2 sr)$	ADM collection by agile spacecraft operations (azimuth rotation)
		Type B uncertainty (accuracy)	of the larger: 0.50 $W/(m^2 sr)$ or 0.5% (k = 1)	Free-flying small satellite with orbit maintainence
		Type A uncertainty (precision)	of the larger: 2.0 W/(m2 sr) or 0.5% (k=1)	Flying with existing coincident imager (< 3 mins apart) 2D point accuracy < 0.2° (goal); < 0.05° threshold
How is climate forcing influenced by varying cloud and aerosol properties?	Shortwave radiances	Spectral Range	0.2 - 3 microns	Ability to view earth's surface, moon, and sun
		Dynamic Range	0 to 425 $W/(m^2 sr)$	iFOV = 0.6° to view moon in one pixel
		Type B uncertainty (accuracy)	larger of 0.50 $W/(m^2 sr)$ or *0.5% (k=1)	gFOV < 25 km
		Type A uncertainty (precision)	of the larger: 0.5 W/(m2 sr) or 0.5% (k=1)	Radiometric stability <0.15% (k = 1) threshold; <0.1% (k = 1) goal *75% (TBD) Earth coverage daily in nominal data collection mode

Figure 2: The Trutinor Science Traceability Matrix. Note that to address the science questions, the observables (SW and LW radiances) must be converted to fluxes using Angular Distribution Models (ADMs). *denotes constraints to be investigated as part of a science study.

Instrument design

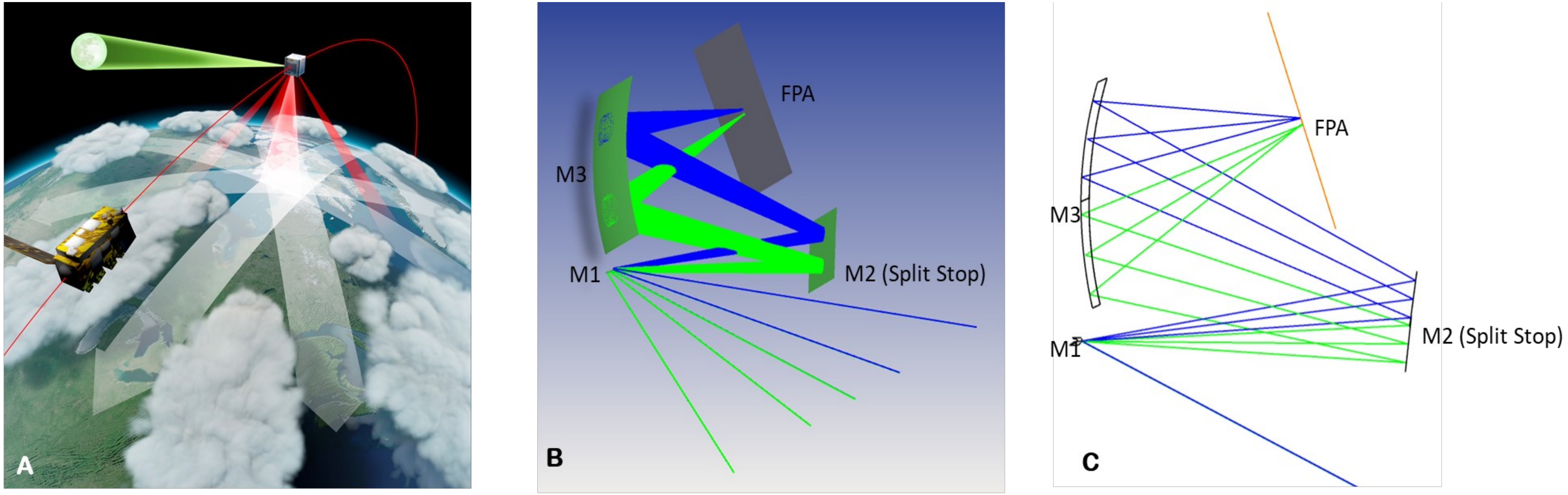


Figure 3: (A) Trutinor observatory, flying in constellation with an imager, performing lunar calibration and collecting multi-angular measurements; (B) and (C) 3D and 2D ray-trace representations of Trutinor optical design, respectively.

TRUTHS

Calibration Options: Shortwave

- Internal Sources, like CERES, OMI:
  - Lamps, current controlled (OMI)
  - Lamps, PD monitored (CERES)

- Vicarious Sources, primary deserts: Lybia-4, Rail Road Valley

- Solar Diffuser, like CERES:
  - No solar diffuser monitor, fast degradation

- Solar Diffuser + Solar Diffuser Monitor, like MODIS/VIIRS/MISR:
  - Can achieve 3% accuracy

- Direct Solar Views with Aperture (0.5mm), like HySICS
  - To be demonstrated

- Direct Lunar View with the same optical path
  - SeaWIFS has best results for relative calibration at 0.12% over 12 years

- **Direct Lunar View with the same optical path**
  - **Absolute calibration to be established by ARCSTONE**

Moon: Potentially Accurate Source for Calibration On-orbit

- **Measurement accuracy is directly related to the information content of the dataset. Measurement accuracy is critical to EOS! Current EOS cannot handle data gaps. Need overlapping observations: CERES, MODIS/VIIRS, Landsats, PACE/SeaWIFS, etc.**

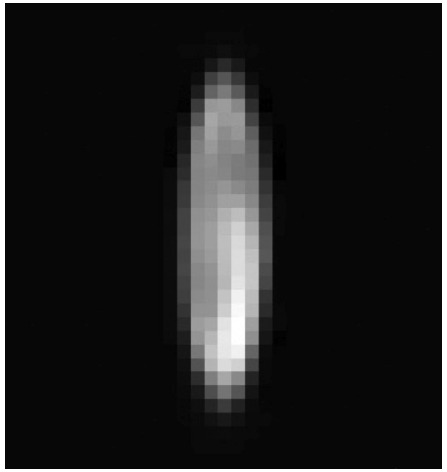
Calibration reference: Lunar Spectral Irradiance (entire disk)

Reflectance of Lunar surface stable to < 10^{-8} / year

- **SeaWiFS gain stability: 0.13% (k=1) over 12 years**
  - **Accuracy of current Lunar Model (ROLO): 5 – 10%**

On-Orbit Calibration Need:

Absolute accurate spectral irradiance for all lunar phase angles and libration states.



Lunar image by SeaWIFS

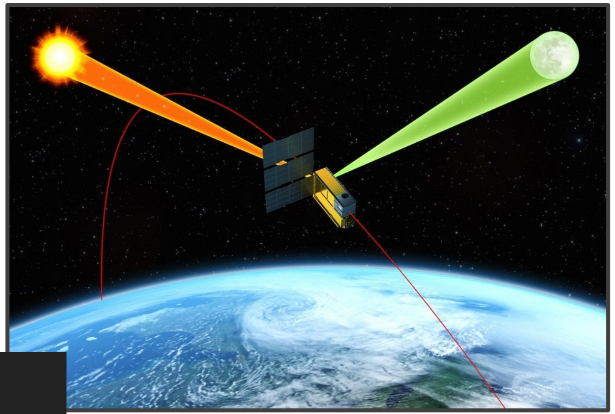
Expected Impacts:
- **Quality of data products**
- **Long-term consistency**
- **Handling data gaps**
- **Reduces instrument size, mass, power**
- **Reduce complexity**
- **Accurate CubeSat sensors**

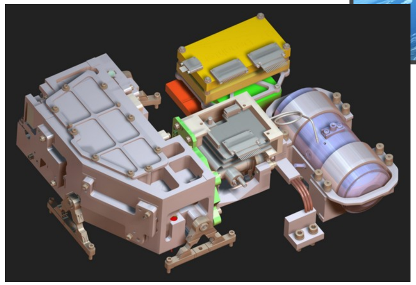
ARCSTONE Objectives:

- *To enable on-orbit high-accuracy absolute calibration for the past, current, and future reflected solar sensors* in LEO and GEO* by providing lunar spectral irradiance as function of satellite viewing geometry and specified wavelength.

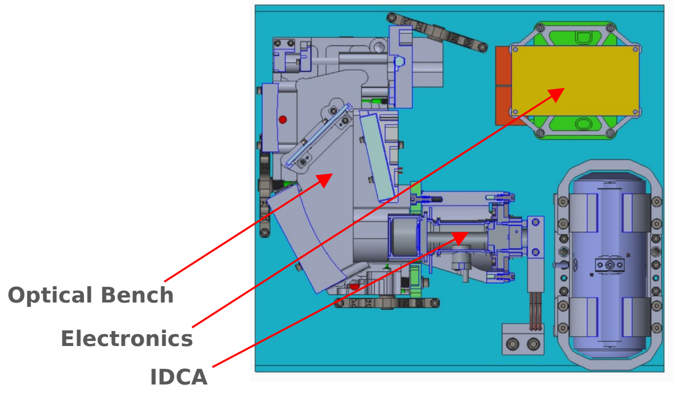
- To design, build, calibrate and validate a prototype instrument, demonstrate *form-fit-function for a 6U observatory with compliance in size, mass, power, and thermal performance*.

* Planetary instruments: OSIRIS Rex Camera suite [Golish et al., 2020]





ARCSTONE Concept: Accurate measurements of Lunar Irradiance from Space with an Instrument flying on 6U CubeSat (courtesy BCT) in LEO.



Progress of ARCSTONE instrument Design

$TRL_{current}$ = 4 TRL_{out} = 5

ARCSTONE Mission Concept

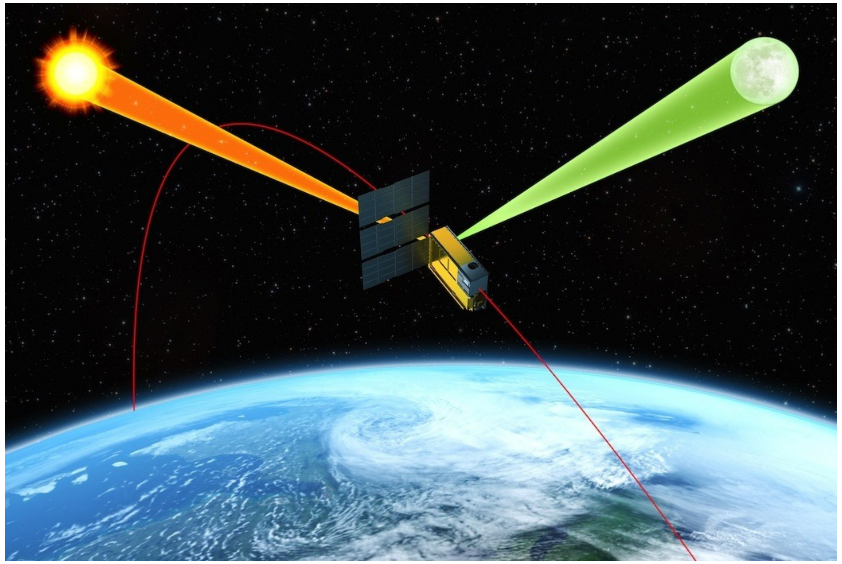
Concept of Operations and Data Products:

- Data to collect: Lunar spectral irradiance every 12 hours, 10 minutes
- Data to collect: Solar spectral irradiance for calibration (daily)
- Combined uncertainty < 0.5% (k=1)
- Spectrometer with single-pixel field-of-view about 0.7° (no scanning !)
- Sun synchronous orbit at 500 – 600 km altitude
- Spectral range from 350 nm to 2300 nm, spectral sampling at 4 nm

1 year: Improvement of current Lunar Calibration Model (factor of 2 – 4);
3+ years: New Lunar Irradiance Model, improved accuracy level (factor of 10).

Key Technologies to Enable the Concept:

- Approach to orbital calibration via referencing Sun (TSIS measurements): Demonstration of lunar and solar measurements with *the same optical path using integration time to reduce solar signal -- Major Innovation !*
- Pointing ability of spacecraft now permits obtaining required measurements *with instrument integrated into spacecraft.*



6U CubeSat Spacecraft Bus:
courtesy of Blue Canyon Technologies (BCT)

BCT 6U XB6 Spacecraft pointing:
Accuracy 0.002° (1-sigma) in 3 axis
Stability 1 arc-sec over 1 sec

ARCSTONE Mission: Key Performance Parameters

Key Parameters	Threshold Value	Goal Value
Accuracy (reflectance)	1.0% (k=1)	0.5% (k=1)
Stability	< 0.15% (k=1) per decade	< 0.1% (k=1) per decade
Orbit	Sun-synch orbit	Sun-synch orbit
Time on-Orbit	1 year	3 years
Frequency of sampling	24 hours	12 hours
Instrument pointing	$< 0.2^{o}$ combined	$< 0.1^{o}$ combined
Spectral Range	380 nm – 900 nm	350 nm – 2300 nm
Spectral Sampling	8 nm	4 nm

* * Threshold Values considered as success criteria

Reference for radiometric requirements (ROLO, T. Stone):
Lunar Phase Angle = 75^{o};
Irradiance = 0.6 (micro W / m^2 nm)
Wavelength = 500 nm

ARCSTONE MISSION CONOPS:

1. Lunar spectral irradiance observations:
- **Every 12 hours**
- **Close to polar locations**
- **Multiple measurements within 5- 10 minutes to improve SNR**

2. Solar Spectral Irradiance observations (solar calibration):
- **Multiple measurements to get required SNR**
- **This is radiometric calibration to the TSIS reference**

3. Dark images:
- **Multiple measurements with closed shutter**
- **Before every lunar and solar observations**

4. Dark field (to calibrate out shutter temp):
- **Multiple measurements of dark space**

5. Field-of-view sensitivity characterization:
- **Calibration of instruments alignment**

6. Spectral calibration:
- **On-board spectral calibration**

7. Spacecraft pointing calibration and other checks:
- **Defined by the BCT for calibration of spacecraft functions**

8. Stand by mode:
- **Mode between observations**

9. Data Downlink Mode

10. Safe Mode (if required)

* 6U CubeSat accommodation Study is completed

Calibration Options: Longwave

- Internal Sources, like CERES, MODIS, VIIRS
  - Blackbody: cavities and plates

- **Internal Sources with melting material cells, like RAVAN, CLARREO IR**
  - **Materials: Hg, Ga, Water**

- Can Moon be used as LW calibration source ?

Detector Technology

- **Thermopile**
  - *Ex. JPL built for RBI (Single/dual diode)*
    - ~8ms, 500 V/W, 1.1nW NEP, Reflectance: 0.94 | 1.16 | 4-20% (VIS, MIR, FIR)
- **Thermistor**
  - *Ex. Hamamatsu 3-5µm, 5-14µm (Linear array)*
    - ~8ms, 65 V/W, 2nW NEP, Reflectance: ~1% to 15% (Aeroglaze Z-306)
- **Microbolometer**
  - ***Ex. BBR 0.25-50µm (30 pixel array)***
    - **~19ms,**
- **(Long term) Graphene Bolometer**
  - *Ex. MIT, LaRC, etc*

Block Diagrams

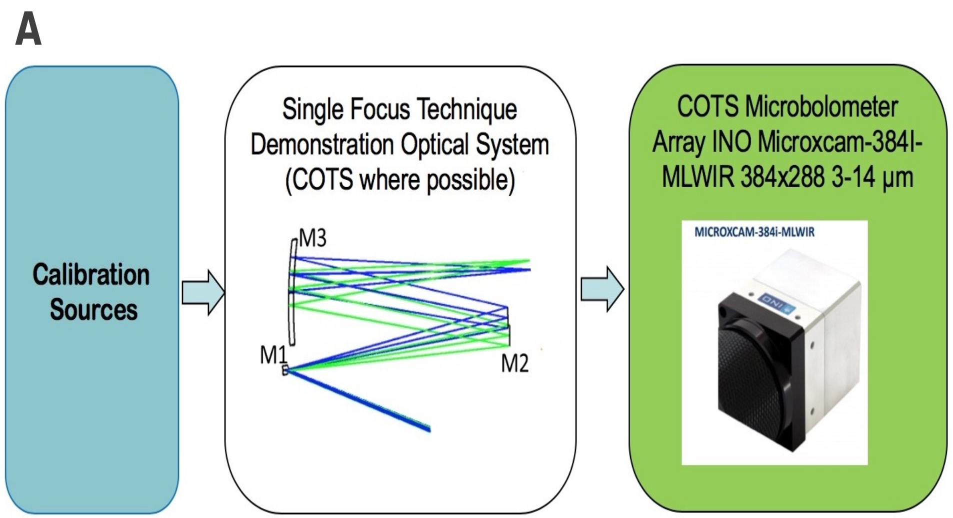
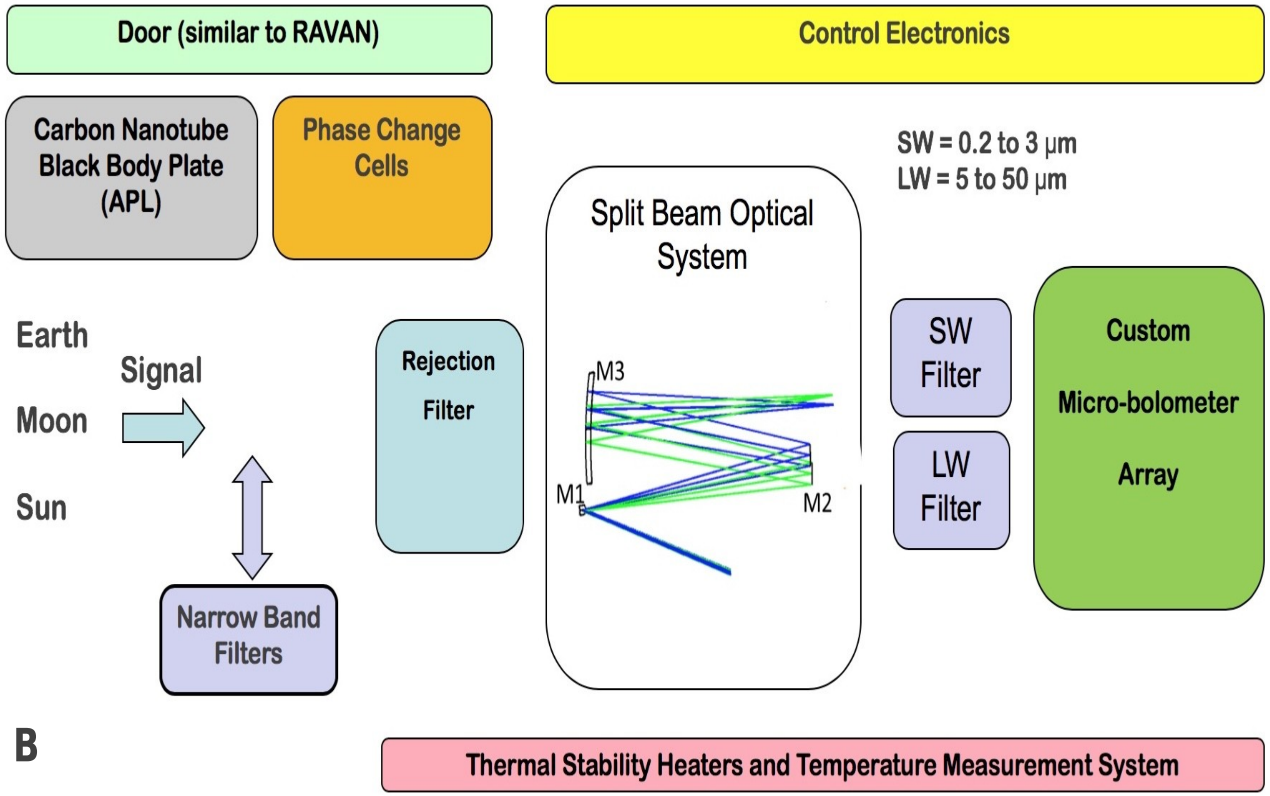


Figure 4: (A) The Trutinor Breadboard diagram;
(B) The Trutinor EDU system block diagram.



Milestones and Progress:

- Developed small sat mission concept (TRL 2)– 100% complete
- Received Center Transformation funds to procure detector– 100% spent
- IRAD FY2020 selected for funding
- ESTO IIP not selected; Team voted to continue IRAD project as planned
- Attended detector training at INO (completed)
- Detector delivered and breadboard design finalized (100% complete)
- Vacuum pump procured and delivered (100% complete)
- Submitted NTR on concept (no patent was pursued)
- First paper on concept in Remote Sensing (100% complete)
- Working with optics vendors to get mirrors (99% of optics received from vendors)
- Plans to characterize microbolometer array (10% complete)
- Plans to assemble breadboard and test it (60% complete)
- Publish 2nd paper on instrument tests (0% complete)

Impacts of COVID-19:

COVID-19 has caused some delays, but has not been a showstopper:

- Could not work with detector at Langley, so we have shipped it to Montana
- Resonon Inc. was working at reduced capacity
- Montana State campus had outbreak problems
- Optical vendors were impacted as well, so there were delays in obtaining mirrors
- LaRC employees cannot visit Resonon/Montana State during detector characterization and breadboard testing
- Cancellation/rescheduling of conferences

Despite some setbacks due to COVID, we believe that we are on track to finish the detector characterization and breadboard testing during Summer 2021.

Publication

remote sensing

MDPI

Letter

Trutinor: a Conceptual Study for a Next-Generation Earth Radiant Energy Instrument

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check for updates

Breadboard Progress

Path Forward

FY19: Trutinor science requirements & trades (IRAD), TRL1

FY19: Trutinor instrument(s) concept & concept review (IRAD), TRL2

FY21: Trutinor concept publication (IRAD)

FY21: Trutinor instrument breadboard & testing (IRAD), TRL3

FY21: IRAD closeout, followed by breadboard test publication

Scientists will continue to do studies on requirements. Additional publications will likely result from these.

Vision for Trutinor's lasting contribution

We believe that maturing Trutinor components and science requirements will be valuable for ERB missions in the future.

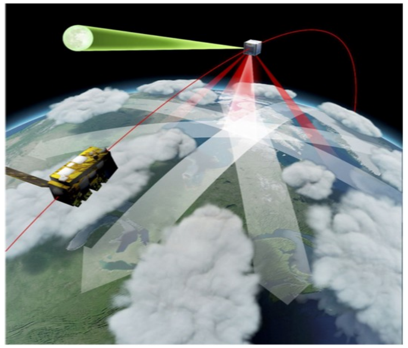
Trutinor: Next-Generation Earth's Radiant Energy Instrument

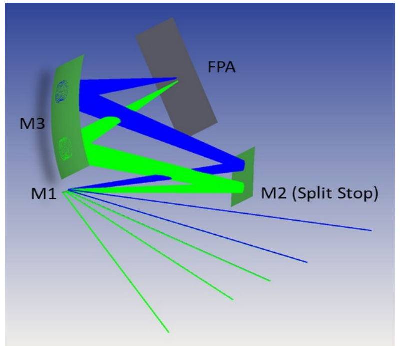
PI: Dr. Cindy Young, NASA LaRC

Objectives:

- Data Gap: Current technology, such as CERES, created an Earth Radiation Budget record by relying on multi-instrument overlap. The accuracy of current instruments is not sufficient to handle a potential data gap, which is very probable with the cancellation of the RBI project.
- Objective: Develop a new compact instrument, capable of flying on a small satellite in formation with imagers in low Earth orbit.
- Objective: Instrument with improved accuracy, SI-traceable measurement uncertainty, and the ability to handle potential gaps in the climate data record.

Trutinor mission concept: Compact Instrument free-flying in formation with an imager.





Trutinor instrument concept: push-broom imaging of Earth in broadband SW and LW channels.

Approach/Innovation:

- Derive science requirements for continuation of the accurate Earth radiation climate record.
- Derive Trutinor measurement requirements.
- Identify mission and instrument design trades.
- Focus on advanced concepts:
  (1) Compact instrument flying on a small satellite in constellation with imagers
  (2) Instrument with improved SI-traceable measurement accuracy on-orbit

Partnerships:

R. Swanson (Resonon, Inc), B. Swartz (APL),
J. Shaw (MT State U), C. Buleri (Quartus Engineering)

End of Year Deliverables

- Breadboard design and build

Next Steps:

- Detector characterization
- Breadboard tests
- Project closeout

Annual IRAD Resources

0.23 FTE, $90 K procurement

$TRL_{start} = 2$ $TRL_{out} = 3$